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6 # HYDROLOGIC AND ECONOMIC SIMULATION OF FLOOD CONTROL ASPECTS OF WATER RESOURCES SYSTEMS.

by

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The general capabilities and recent applications of The Hydrologic Engineering Center's computer model titled "Simulation of Flood Control and Conservation Systems" (HEC-5C) are presented. The need for and the general capabilities of the model for detailed hydrologic and economic simulation of all types of water resource projects for flood damage reduction are stressed. The use of the model for planning studies that include alternatives such as reservoirs, levees, channel modifications, flood proofing, evacuation, and land use

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Recent applications of the model in planning studies for several river basins are described. Comments on work underway to use the model for day-to-day reservoir systems are offered.

INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH

WATER RESOURCES SYSTEMS (Subject D.C.)

Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems[1]

by Bill Scott Eichert

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Synopses:

The general capabilities and recent applications of The Hydrologic Engineering Center's computer model titled "Simulation of Flood Control and Conservation Systems" (HEC-5C) are presented. The need for and the general capabilities of the model for detailed hydrologic and economic simulation of all types of water resource projects for flood damage reduction are stressed. The use of the model for planning studies that include alternatives such as reservoirs, levees, channel modifications, flood proofing, evacuation, and land use controls are described.

Recent applications of the model in planning studies for several river basins are described. Comments on work underway to use the model for day-to-day reservoir operation during flood emergencies for existing flood control reservoir systems are offered.

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[1]Presented at the XVIth International IAHS conference, Sao Paulo, Brazil, August 1975.

1. Need for a Flood Control Simulation Model

Because of the great expenditure of funds required to construct structures to reduce flooding in a river basin, it is important to make sure that each project built is justified and is more desirable than other alternatives. In a complex river basin where numerous system components exist or are required to reduce flooding, the evaluation of each alternative requires a large number of calculations. Until recently all such evaluations had to be done by rather crude techniques or by laborious manual procedures, although a few simple computer models could be used on parts of the study.

2. Purpose of Simulation Model -- HEC-5C

The HEC-5C program ("Simulation of Flood Control and Conservation Systems") was developed to assist in planning studies required for the evaluation of proposed changes to a system and to assist in sizing the system components for flood control and conservation requirements for each component recommended for the system. The program can be used in studies made immediately after a flood to calculate the preproject conditions and to show the effects of existing and/or proposed reservoirs on flows and damages in the system. The program should also be useful in selecting the proper reservoir releases throughout the system during flood emergencies in order to minimize flooding as much as possible and yet empty the system as quickly as possible while maintaining the proper balance of flood control storage among the reservoirs.

The above purposes are accomplished by economically and hydrologically simulating the sequential operation of various system components of any configuration for short interval historical or synthetic floods or for long duration nonflood periods, or for combinations of the two. Specifically the program may be used to determine:

a. Flood control and conservation storage requirements of each reservoir in the system.

b. The evaluation of operational criteria for both flood control and conservation for a system of reservoirs.

c. The determination of the system of existing and proposed reservoirs or other structural or nonstructural alternatives that result in the maximum net benefit for flood control for the system by making simulation runs for selected alternative systems.

While the HEC-5C model can be used in simulation of reservoir systems for water conservation and hydropower purposes on monthly routings, this paper will focus only on the flood control aspects of the program.

3. Computer Requirements

The program, written in FORTRAN IV, was developed on a UNIVAC 1108 computer with 64,000 words of storage. The UNIVAC version can simulate the operation of 15 reservoirs, 25 control points, 5 diversions, and 9 power plants, using up to 50 time periods in each flood event. Dimension limits have been increased for a CDC 7600 computer which allows the simulation of 35 reservoirs, 75 control points, 11 diversions, and 9 power plants for up to 100 time periods for each runoff event.

4. General Capabilities of Program

The program can be used on a system with any configuration since the location of each system component is described by input data. The dimension

limits of the program, for items like number of reservoirs and number of control points, may be easily changed to accommodate extremely large systems or to reduce core storage for smaller systems.

Reservoirs simulated by the program can have either gated or uncontrolled flood control outlets. Those reservoirs with gated outlets can be operated for one or more downstream locations to minimize flooding for a predetermined number of time periods (input data) based on input inflows and considering a specified percentage for forecast error. Reservoirs with uncontrolled flood outlets cannot be operated, but their effect is properly evaluated based on routings with known inflows and where the outflows are a function of the reservoir storages. All reservoirs are kept in balance as much as possible without causing downstream flooding and without violating minimum releases and reservoir release rate of change constraints. Emergency reservoir releases are simulated by several optional routines such that the reservoirs make releases that contribute to flooding when they exceed, or are forecasted to exceed (optional), their available flood control storage. Reservoir outflows can be specified by input for any reservoir for any or all time periods, and the other reservoirs will adjust their releases as required to minimize the downstream flooding.

A single diversion can be made <u>from</u> any control point and may be routed to any other location in the system. Any number of diversions can be routed <u>to</u> a specific control point. Diversions can be made which are (a) constant for the entire flood or (b) functions of reservoir storage or (c) functions of inflows.

The program will calculate average annual damages for any or all control points (nonreservoirs) using one or more ratios for each of several historical or synthetic floods as described in reference 1. Damages for one or more specific simulated floods can be computed (instead of average annual damages) on the assumption that damages can be expressed as a direct function of peak discharge or stage. Modifications are underway to allow damages to vary with season and duration of flooding. Damages or average annual damages will be computed for natural or unregulated conditions, for regulated conditions (due to the reservoir system assumed), and for uncontrolled local flow conditions (which assumed that unlimited flood control storage was available at each reservoir site). If a proposed system contains existing reservoirs, the damage reduction can be evaluated from a base condition which is for the existing system.

Average annual damages, costs and system net benefits for flood damage reduction can also be evaluated for nonreservoir alternatives such as levees, channel improvements and nonstructural alternatives (flood proofing, relocation, flood plain zoning, etc.).

5. Reservoir Operational Criteria

Reservoirs are operated to satisfy constraints at individual reservoirs, to maintain specified flows at downstream control points, and to keep the system in balance. Constraints at individual reservoirs are as follows:

a. When the level of a reservoir is between the top of conservation pool and the top of flood pool, releases are made to attempt to draw the reservoir to the top of conservation pool without exceeding the designated channel capacity at the reservoir or at downstream control points for which the reservoir is being operated.

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1. HEC-5C "Simulation of Flood Control and Conservation Systems," Users Manual, The Hydrologic Engineering Center, U. S. Army Corps of Engineers, November 1974.

b. Releases are made equal to or greater than the minimum desired flows when the reservoir storage is greater than the top of buffer storage, and or equal to the required flow if between level one and the top of buffer pool. No releases are made when the reservoir is below level one (top of inactive pool). Releases calculated for hydropower requirements will override minimum flows if they are greater than the controlling desired or required flows.

c. Releases are made equal to or less than the designated channel capacity at the reservoir until the top of flood pool is exceeded, then all excess flood water is dumped if sufficient outlet capacity is available. If insufficient capacity exists, a surcharge routing is made. Input options permit channel capacity releases (or greater) to be made prior to the time that the reservoir level reaches the top of the flood pool if forecasted inflows are excessive.

d. The reservoir release is never greater (or less) than the previous period release plus (or minus) a percentage of the channel capacity at the dam site unless the reservoir is in surcharge operation.

Operational criteria for specified downstream control points are as follows:

a. Releases are not made (as long as flood storage remains) which would contribute to flooding at one or more specified downstream locations during a predetermined number of future periods except to satisfy minimum flow and rate-of-change of release criteria. The number of future periods considered is the lesser of the number of reservoir release routing coefficients or the number of local flow forecast periods.

b. Releases are made, where possible, to exactly maintain downstream flows at channel capacity (for flood operation) or for minimum desired or required flows (for conservation operation). In making a release determination, local (intervening area) flows can be multiplied by a contingency allowance (greater than 1 for flood control and less than 1 for conservation) to account for uncertainty in forecasting these flows.

Operational criteria for keeping a reservoir system in balance are as follows:

a. Where two or more reservoirs are in parallel operation above a common control point, the reservoir that is at the highest index level, assuming no releases for the current time period, will be operated first to try to increase the flows in the downstream channel to the target flow. Then the remaining reservoirs will be operated in a priority established by index levels to attempt to fill any remaining space in the downstream channel without causing flooding during any of a specified number of future periods.

b. If one of two parallel reservoirs has one or more reservoirs upstream whose storage should be considered in determining the priority of releases from the two parallel reservoirs, then an equivalent index level is determined for the tandem reservoirs based on the combined storage in the tandem reservoirs.

c. If two reservoirs are in tandem (one above the other), the upstream reservoir can be operated for control points between the two reservoirs. In addition, when the downstream reservoir is being operated for control points, an attempt is made to bring the upper reservoir to the same index level as the lower reservoir based on index levels at the end of the previous time period.

6. Multiflood Selection and Operation

The selection of the floods used in operating the system, is of paramount importance in the determination of the average annual damages. The floods

selected must generate the peak flows at the damage centers (particularly the key ones) which represent the full range of the flow-frequency-damage relationship for base conditions as well as for modified conditions.

Even using all historical floods of record may introduce some bias in the average annual damage if most historical floods centered over a certain part of the basin by chance and not over other areas. For instance one dam site may have several severe historical floods while another dam site immediately adjacent to that area may, due to chance, not have had any severe floods.

While it is possible in the program, HEC-5C, to use only a single flood and several ratios of that flood in computing average annual damages, this procedure could introduce considerable bias in the results. It would be far better to use several historical floods with storm centerings throughout the basin and to use several ratios of those floods to obtain flows at the damage centers representing the full range of the flow-frequency-damage relationship for base conditions and for regulated conditions.

Studies are currently being made at The Hydrologic Engineering Center to help establish criteria for the selection of the floods and ratios to use.

7. Evaluation of Alternative Reservoir Systems

If this computer program is to be used to evaluate proposed reservoirs, then the data cards should be assembled so that all proposed reservoirs are included, even if some of them would serve as alternatives of others. Control points should be selected and coded for all damage centers, control points for reservoir operation, and information points. Once the entire system is coded, a single card can be used to delete reservoirs from the system for each alternative system selected. This card can be used to delete any reservoir in the system except for downstream tandem reservoirs (these reservoirs can be deleted by removing the reservoir cards). Flood damages (or average annual flood damages) can be evaluated at any number of control points. Reservoir costs can also be evaluated by showing how the costs vary with reservoir storage based on the top of flood control storage. If costs and average annual flood damages are calculated, the net system flood benefits will be printed out for each alternative system operated. By careful selection of alternative systems, the system that produces the maximum net flood benefits can be determined by a reasonable number of separate computer runs.

8. Evaluation of Nonreservoir Alternatives

Structural and nonstructural alternatives to certain reservoirs can also be evaluated in the system simulation with or without reservoirs in the system. The existence of a levee or channel improvement can be reflected in the reservoir system operation by changing the channel capacity if appropriate. Only one set of routing criteria can be read for each reach and thus the natural and modified routings will use the same criteria. This fact requires that when the routing criteria is different between natural and modified conditions, the natural flows and corresponding damages must be calculated by a separate computer run and entered on input cards as the base condition damages for the computer runs for various proposed modifications. Costs of nonreservoir alternatives can be shown as functions of the channel discharges. For a given design discharge an interpolation is made to determine the capital cost applicable to the control point. The average annual flood damages can be evaluated in the same manner as for reservoir alternatives. However, the zero damage point can be automatically changed to the design discharge for modified conditions if a control point cost card is read. Two sets of damage cards can be read as an alternative to the above procedure, in representing natural and regulated conditions, so that the entire damage curve can be changed for regulated conditions.

Nonstructural alternatives (flood proofing, flood plain zoning, etc.) can be handled in the same manner as structural alternatives (usually by using two sets of damage cards), however the nonstructural alternative will require defining the upper limit of the flood proofing, zoning, etc., as a channel capacity or design discharge.

9. Use of HEC-5C in Flood Control System Selection

Approximately 12 reservoir systems have been simulated using HEC-5C (Table 1). Most of these systems have used the flood control version which was released in May 1973.[2] The version which also includes conservation operation (HEC-5C) has not been officially released yet, but it has been used for flood control simulation and average annual damages have been calculated for the Susquehanna, Red River of the North, and the Grand (Neosho) River basins. Monthly conservation operation has been used on the Pajaro River, the Red River of the North, the Hudson River Basin, the Little River basin and several hypothetical systems. Of the studies conducted to date by HEC using this model, five of them have been for preliminary planning studies and have been used for the sole purpose of determining the regulated flows throughout the basin for various historical and synthetic floods. Each one of these basins also had a HEC-1[3] rainfall-runoff data model developed in order to calculate the runoff from synthetic floods and to use rainfall to get a better distribution of runoff for historical floods. The study of the 15 reservoir system for the Trinity River was made in connection with Design Memorandum studies for the Tennessee Colony reservoir in order to determine the flood control storage in that downstream project (14 reservoirs above it) and to evaluate various alternative plans of channel improvements below the project. The work on the existing five reservoir Merrimack basin is expected to use HEC-5 in a real-time operation mode using forecasting routines and automatic data collection by December 1975.

The Susquehanna River Basin has 12 reservoirs existing or under construction, and another 22 potential reservoir sites are being investigated along with other structural and nonstructural alternatives in a preliminary planning study being conducted by the Baltimore District office of the Corps, the HEC and a private consulting firm Anderson-Nichols of Boston, Massachusetts. The decision for selection of the desired system will make important use of the average annual damage reduction and net benefits of the alternative systems which will be printed out for each alternative evaluated by HEC-5C.

10. Strategy for Selection of Alternative Systems

For systems with only a few possible components the strategy for determining the best alternatives can be quite simple since each possible alternative can be evaluated. For systems with a large number of possible alternatives, the strategy can be difficult to predetermine and the best available procedure to follow may be to simply select alternatives to be evaluated one at a time following a careful review of information obtained from previous runs.

Certain economic criteria should be observed for the final system selected. The incremental cost of the new components of the proposed system should be less than the damage reduction accomplished by the new components. In addition, each

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2. HEC-5 "Reservoir System Operation for Flood Control," Users Manual, The Hydrologic Engineering Center, U. S. Army Corps of Engineers, May 1973.
3. HEC-1,"Flood Hydrograph Package," Users Manual, The Hydrologic Engineering Center, U. S. Army Corps of Engineers, January 1973.

project must be justified on the basis of the last increment added. That is to say, the annual cost of each project must be less than the difference between the average annual damages of the proposed system with and without that project.

A certain minimum performance criteria is also necessary. This philosophy says that if a certain level of protection cannot be provided by the system then it would be better not to build any structures than to give the public a sense of false security.

With the above ideas in mind it seems necessary to first determine a minimum system that will provide an acceptable level of protection. Next see if various alternatives can be used to get a larger value of the maximum net benefits. When the maximum net benefits appears to be obtained (and it is positive) then each project should be deleted in turn to see if that project prevented more damages than it cost to build. The process of maximizing the net benefits by selecting alternatives and evaluating using HEC-5C, at present, can only be based on good engineering judgment. After a few studies are completed using this new tool, perhaps more definite guidance will be available.

11. Conclusions

It appears that the HEC-5C simulation model should be a useful tool for planners to evaluate the effects of water resource projects and nonstructural alternatives in most river basins because it can accurately, quickly, and inexpensively simulate the hydrologic and economic responses of the system. While much of the detailed analysis of hydrology, reservoir regulations, and economics can be accomplished by the model, considerable engineering ingenuity will be required to insure that the proper data is used in the model, that the model is giving valid results, and that the proper sequence of alternatives are evaluated in order to determine the best plan for the reduction of damages in a basin.

It also seems probable that the model will be useful for simulating multipurpose reservoir operation. In this connection considerable work will be required to develop economic and social parameters to allow multipurpose evaluation of the system alternatives similar to flood control.

Considerable experience and research will be required to develop procedures, techniques and/or optimization subroutines which will enable the program to be used in the most efficient manner in the selection of the best multipurpose alternatives for the basin.

TABLE 1

SYSTEMS SIMULATED BY HEC-5C

River Basin	Location	Number Reservoirs	Number Control Points (including res)	Time Increment (hrs)	Approximate Drainage Area (square miles)
1. Trinity	Texas	15	28	24	18,000
2. Merrimack	New England	5	11	3	4,400
3. Susquehanna	Pennsylvania	34	75	4	24,000
4. Schulkill	Pennsylvania	12	26	3	1,900
5. Potomac	Virginia Maryland Pennsylvania	26	39	2	12,000
6. Red River of North	Minnesota	13	29	24 720	40,000
7. Feather	California	3	4	2	5,900
8. Pajaro	California	3	6	1 720	400
9. Grand (Neosho	Oklahoma	24	86	2	5,900
10. James	Virginia	22	35	6	6,800
11. Red River 1st Phase	Texas Arkansas	14	28	6	12,000
12. Hudson	New York Pennsylvania	3	5	720	500